# CUTTINGS LIFTING IMPROVEMENT OF DIFFERENT DRILLED CUTTING SIZES USING POLYPROPYLENE BEADS WITH AND WITHOUT PIPE ROTATION

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# ABSTRACT

Directional wells become a successful field-development method to meet higher energy demands worldwide and to increase the recovery factor. However, the most challenging problem encountered in drilling such wells is inefficient wellbore cleaning. Therefore, this study was conducted to investigate the performance of polypropylene copolymer (PP) beads in water-based mud to hamper the wellbore cleaning issue. The study includes sample characterization and investigation of the effect on mud rheological and filtration properties. The presence of ethylene in the PP beads composition has led to an increase in their melting point up to 159°C (318°F), which is higher than typical reservoir temperature reported in Malay Basin. Therefore, the mud rheological and filtration properties tests were conducted up to 250°F only. Also, the PP beads were discovered to degrade at 278.59°C (533.46°F). The effect of hole cleaning have been scrutinized using a flow loop test section (20-ft of transparent PVC having a 3.042-inch ID simulated as wellbore, and a rotatable Class B carbon steel with 1.346-inch OD which simulates a drill pipe) and were compared with basic water-based mud (WBM) at various wellbore inclination angles (from 0° to 90°) and pipe rotation speed (from 0 to 150 rpm). The experimental work was executed using several PP beads concentrations (from 0 to 10 ppb), which were introduced in water-based mud, and their performances were compared with basic WBM in terms of rheological properties and cuttings transport performance (CTP). CTP is an extent measure to lift unwanted cuttings out of the wellbore and was performed by employing 0.25% (by volume) of different cutting sizes, ranging from 0.5 to 4.0 mm, in the prepared mud. The comparison also made based on PP beads concentration, cutting sizes, wellbore angles, and pipe rotation speed with basic WBM. The experimental results showed that the rheological properties are slightly increased when mingling the PP beads with mud, and the opposite outcome was obtained for filtration properties. Furthermore, the CTP improved once commingled with PP beads for all different cutting sizes and hole angles due to the buoyancy and impulsive effects. This experiment also detects the critical angle between 30° to 60°, which indicates by decreasing of CTP and the lowest CTP was found at 60°. Since buoyancy and impulsive force at the horizontal hole is negligible, a combination effect of pipe rotation, mud rheology (mud viscosity of 15 cP) and flow regime (turbulent flow) has rendered improvement towards lifting performance. Besides, smaller cuttings appeared to be easier to be transported compared to the larger cuttings in both vertical and deviated wells, for each rotary speed and drilling muds. Additionally, pipe rotation contributes to cuttings transport by increasing the CTP for all experimental variables. Conclusively, the presence of PP beads in the mud has reduced the cuttings concentration in the wellbore for all cutting sizes and hole angles, and thereby enhances the CTP. Henceforth, making the PP beads a promising additive for drilling mud in lifting drilled cuttings out of the hole effectively.

# ABSTRAK

Telaga berarah menjadi kaedah yang berjaya dalam medan pembangunan bagi memenuhi permintaan tenaga yang tinggi di seluruh dunia dan meningkatkan faktor perolehan. Walau bagaimanapun, masalah yang paling mencabar yang dihadapi dalam penggerudian telaga ialah ketidakcekapan dalam pembersihan lubang telaga. Oleh itu, kajian ini dilaksanakan untuk mengkaji prestasi manik kopolimer polipropilena (PP) dalam lumpur dasar air untuk menghalang masalah pembersihan lubang telaga. Kajian termasuk pencirian sampel dan kesannya terhadap sifat-sifat reologi lumpur dan penurasan. Kehadiran etilena dalam komposisi PP manik telah membawa kepada peningkatan kadar lebur sehingga 159°C (318°F), lebih tinggi daripada suhu reservoir di Lembangan  Melayu. Oleh itu, ujian sifat reologi lumpur dan penurasan telah dilaksanakan sehingga 250°F sahaja. Juga, manik PP didapati merosot pada 278.59°C (533.46°F). Kesan pembersihan lubang telah diteliti menggunakan seksyen ujian gelung aliran (20-kaki PVC lutsinar yang berdiameter 3.042-inci bagi mensimulasikannya sebagai telaga dan keluli karbon Kelas B berputar dengan diameter luar 1.346-inci disimulasi sebagai paip gerudi) dan dibandingkan dengan lumpur dasar air (WBM) pada pelbagai sudut kecondongan telaga (dari 0° sehingga 90°) dan kelajuan putaran paip (dari 0 sehingga 150 rpm). Uji kaji dilaksana menggunakan beberapa kepekatan PP (dari 0 hingga 10 ppb), yang dicampurkan dengan lumpur dasar air, dan prestasinya dibandingkan dengan WBM dari segi sifat reologi dan prestasi pengangkutan rincisan (CTP). CTP ialah ukuran bagi keupayaan mengangkut keratan yang tidak diingini keluar dari lubang telaga dan dilaksana dengan menggunakan 0.25% (berdasarkan isipadu) jumlah rincisan pelbagai saiz, dari 0.5 mm sehingga 4.0 mm, dalam lumpur yang disediakan. Perbandingan juga dibuat berdasarkan kepekatan PP, saiz keratan, sudut lubang telaga, dan kelajuan putaran paip dengan WBM. Hasil ujikaji menunjukkan bahawa sifat reologi sedikit meningkat apabila manik PP bercampur dengan lumpur, dan hasil yang bertentangan diperoleh bagi sifat penurasan. Tambahan pula, CTP bertambah baik apabila bercampur dengan manik PP untuk semua saiz rincisan dan semua sudut lubang berikutan kesan keapungan dan impulsif. Kajian turut mengenal pasti sudut kritikal iaitu dari 30° sehingga 60° yang menyebabkan berlakunya penurunan CTP dengan CTP paling rendah berlaku pada 60°. Memandangkan daya keapungan dan impulsif pada lubang mendatar adalah kecil, kesan kombinasi putaran paip, reologi lumpur (kelikatan lumpur 15 cP) dan rejim aliran (aliran bergelora) telah meningkatkan prestasi pengangkatan. Selain itu, rincisan yang lebih kecil kelihatan lebih mudah untuk diangkut berbanding rincisan yang lebih besar bagi kedua-dua telaga tegak dan condong pada semua kelajuan berputar dan lumpur gerudi. Selain itu, putaran paip menyumbang kepada pengangkutan rincisan dengan meningkatnya CTP untuk semua pembolehubah eksperimen. Kesimpulannya, kehadiran manik PP dalam lumpur telah mengurangkan kepekatan rincisan dalam lubang telaga bagi semua saiz rincisan dan sudut lubang, dan dengan itu meningkatkan CTP. Seterusnya, menjadikan manik PP sebagai bahan tambah lumpur yang berpotensi besar bagi mengangkut rincisan gerudi keluar dari lubang secara berkesan.

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| | | |
|---|---|---|
| API | - | American Petroleum Institute |
| AV | - | Apparent Viscosity |
| CCI | - | Cutting Carrying Index |
| CFD | - | Computational Fluid Dynamics |
| CFR | - | Minimum Cuttings Flow Rate |
| CTE | - | Cuttings Transport Efficiency |
| CTP | - | Cuttings Transport Performance |
| CTR | - | Cuttings Transport Ratio |
| ECD | - | Equivalent Circulating Density |
| FTIR | - | Fourier Transform Infrared Spectroscopy |
| GS | - | Gel Strength |
| HDPE | - | High-Density Polyethylene |
| HPHT | - | High Pressure High Temperature |
| ID | - | Internal Diameter |
| JDA | - | Joint Development Area |
| LDPE | - | Low-Density Polyethylene |
| MSDS | - | Material Safety Data Sheets |
| MTV | - | Minimum Transport Velocity |
| MW | - | Mud Weight (Mud Density) |
| NPS | - | Nominal Pipe Size |
| NPT | - | Non-Productive Time |
| OBM | - | Oil-Based Mud |
| OD | - | Outer Diameter |
| PE | - | Polyethylene |
| PP | - | Polypropylene Copolymer Beads |
| PV | - | Plastic Viscosity |
| PVC | - | Polyvinyl Chloride |
| ROP | - | Rate of Penetration |
| SWG | - | Standard Wire Gauge |
| TGA | - | Thermogravimetric Analysis |

| | | |
|---|---|---|
| TI | - | Transport Index |
| VSD | - | Variable Speed Drive |
| WBM | - | Water-Based Mud |
| YP | - | Yield Point |
| YP/PV | - | Yield point to plastic viscosity ratio |

## LIST OF SYMBOLS

| | | |
|---|---|---|
| $\theta_{300}$ | - | 300-rpm reading (rheometer) |
| $\theta_{600}$ | - | 600-rpm reading (rheometer) |
| $g$ | - | Acceleration due to gravity |
| $a$ | - | Acceleration of an object |
| $A_{an}$ | - | Annular area |
| $v_{an}$ | - | Annular velocity |
| A | - | Area |
| $v_{mean}$ | - | Average maximum velocity |
| $F_b$ | - | Buoyancy force |
| $K_c$ | - | Casson plastic viscosity (Casson model constant) |
| $\tau_{yc}$ | - | Casson yield stress |
| $\rho_c$ | - | Cuttings density |
| $d_c$ | - | Cuttings diameter |
| ° | - | Degree |
| °C | - | Degree Celsius |
| °F | - | Degree Fahrenheit |
| $\rho_p$ | - | Density of polymer beads |
| $\emptyset$ | - | Diameter |
| $d$ | - | Diameter of PP beads |
| $\Delta v$ | - | Difference between fluid velocity and polymer beads velocity |
| $C_D$ | - | Drag coefficient |
| $F_D$ | - | Drag force |
| $d_p$ | - | Drill pipe diameter |
| $Q$ | - | Flow rate |
| $\rho_f$ | - | Fluid density |
| $n$ | - | Fluid flow behaviour index |
| F | - | Force |
| $f_s$ | - | Friction coefficient between cuttings and annular wall under "wet" condition |

| | | |
|---|---|---|
| $F_f$ | - | Frictional force |
| $F_g$ | - | Gravitational force |
| $K$ | - | Herschel-Buckley fluid consistency index |
| $\theta$ | - | Hole angle |
| $d_h$ | - | Hole diameter |
| $F_{imp}$ | - | Impulsive force |
| $v_i$ | - | Initial velocity |
| $S$ | - | Length of test section |
| $C_L$ | - | Lift coefficient |
| $F_L$ | - | Lift force |
| $m_c$ | - | Mass of cuttings |
| $m_p$ | - | Mass of polymer bead |
| $v_{max}$ | - | Maximum velocity |
| $F_{net}$ | - | Net force |
| $v_t$ | - | Net velocity |
| $N_{Re}$ | - | Particle Reynolds number |
| $v_{sl}$ | - | Particle settling velocity |
| $\mu_p$ | - | Plastic viscosity |
| $KBr$ | - | Potassium Bromide |
| $k$ | - | Power Law consistency coefficient |
| $P$ | - | Pressure gradient |
| $v_c$ | - | Representative velocity of the fluid in the vicinity of the particles (Cuttings velocity) |
| $F_{ga}$ | - | Resolved gravitational force parallel to hole axis |
| $F_{gva}$ | - | Resolved gravitational force perpendicular to hole axis |
| $F_{axial}$ | - | Resultant force in axial direction |
| $A$ | - | Robertson-Stiff consistency index |
| $B$ | - | Robertson-Stiff fluid flow behaviour index |
| $\gamma$ | - | Shear rate |
| $C$ | - | Shear rate correction factor |
| $\gamma_y$ | - | Shear rate in Robertson-Stiff model |
| $\tau$ | - | Shear stress |
| SG | - | Specific gravity |

| | | |
|---|---|---|
| $t$ | - | Time taken |
| $*$ | - | Unknown value |
| $v_f$ | - | Velocity final |
| $v_p$ | - | Velocity of polymer bead |
| $\mu$ | - | Viscosity |
| $V_p$ | - | Volume of polymer beads |
| $W$ | - | Weight |
| $\tau_y$ | - | Yield point or yield stress |

## LIST OF UNITS

| | | |
|---|---|---|
| $cP$ | - | Centipoise (unit of viscosity) |
| $cm^3$ | - | Cubic centimetre (volume unit) |
| $ft^3/s$ | - | Cubic feet per second (unit of flow rate) |
| $m^3/s$ | - | Cubic metre per second (unit of flow rate) |
| $ft/hr$ | - | Feet per hour |
| $ft$ | - | Foot |
| $ft/s$ | - | Foot per second |
| $gpm$ | - | Gallons per minute (unit of flow rate) |
| g | - | Gram |
| $hp$ | - | Horsepower |
| $kg/m^3$ | - | Kilogram per cubic metres (unit of density) |
| $kW$ | - | Kilowatt (unit of power) |
| $l$ | - | Litres |
| $m$ | - | Metre |
| $m/hr$ | - | Metre per hour |
| $m/s$ | - | Metre per second (unit of velocity) |
| $m/s^2$ | - | Metre per square seconds (unit of acceleration) |
| $ml$ | - | Millilitres |
| $mm$ | - | Millimetre |
| $mPa \cdot s$ | - | Millipascal-second |
| $N$ | - | Newton |
| $N/m^2$ | - | Newton per square metres |
| $Ns/m^2$ | - | Newton-seconds per square metres |
| $ppb$ | - | Parts per billion (unit of concentration) |
| $Pa$ | - | Pascal |
| $Pa/m$ | - | Pascal per metre |
| $Pa \cdot s$ | - | Pascal-second |
| $dynes/cm^2$ | - | Poise |
| $lb/in^3$ | - | Pound per cubic inch |

| | | |
|---|---|---|
| $ppg$ | - | Pound per gallon (unit of density) |
| $pcf$ | - | Pound-force per cubic foot (unit of material density) |
| $psi$ | - | Pound-force per square inch (unit of pressure) |
| lb/100 $ft^2$ | - | Pounds per hundred square feet |
| $cm^{-1}$ | - | Reciprocal centimetres (unit of wavenumber) |
| $sec^{-1}$ | - | Reciprocal seconds |
| $rpm$ | - | Revolutions per minute |
| $s$ | - | Seconds |
| $V$ | - | Volt (unit of voltage) |

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# CHAPTER 1

# INTRODUCTION

This preliminary chapter offers a quick overview of the whole thesis content. The chapter begins with a brief background on the advancement of new drilling technology, which has been taking place since the beginning of petroleum history, including designing new drilling fluids. As the petroleum exploration and production operations keep going, the directional drilling becomes a great pace to meet the market demands. However, many problems have been encountered, and one of the most significant challenges facing by the crews is wellbore cleaning, which becomes the main interest and ground to this research work. The following section described the problem to be investigated, the aims of the study to be achieved, and what works or tests that should be done and not to be done, which are described in the scope and limitation sections. The importance and the solution to the gap of literature on wellbore cleaning are delineated in the following section.

## 1.1 Background of Study

In the past decade, technology advancement is not all simply random evolutionary advances, yet represent a step-change in drilling technology. These technologies breakthrough have shifted the older cable-tool drilling to the rotary drilling techniques, which have been employed until now (Inglis, 2013). The rotary drilling techniques cannot produce a satisfactory cost-effective drilling operation alone but have to be complemented by other imperative components, and drilling fluid circulation is no exception to such contributions. Therefore, the circulation of drilling fluid becomes an integral part in optimizing a drilling operation (Adari *et al.*, 2000).

Among the numerous functions performed by drilling fluid, the most significant is its ability to transport drilled cuttings generated by a bit from the bottom of the borehole, through the annulus space between the drill pipe and the wellbore's wall, up to the surface, which is referred to as the carrying capacity of the muds (Williams and Bruce, 1951). The term of carrying capacity is also called as cuttings lifting capacity (Samsuri and Hamzah, 2011). Failure to withdraw the unwanted cuttings out of the hole efficiently may lead to several expensive drilling problems, namely bit wear, wellbore enlargement, high torque and drag, poor cementing jobs, slow drilling rate, increased equivalent circulating density, lost circulation, and for the worst case, drill pipe sticking may occur (Adari *et al.*, 2000; Samsuri and Hamzah, 2011; Egenti, 2014). It may result in side-tracking or complete loss of the well. However, the most critical of these is the pipe sticking, as this problem requires a costly remedy (Adari *et al.*, 2000).

The increased demand for petroleum from time to time and coupled with the technology advancement has led to more exploration activities in remote and hostile areas as a part of enhanced recovery from reservoirs. Some of these targets can only be achieved via deviated or horizontal holes. Therefore, the directional drilling becomes more favourable to reach a pre-determined target in the earth's crust, which typically may not be accessed by vertical drilling, especially to thin and tight reservoirs (Inglis, 2013). When dealing with a near-vertical hole, some minor complications may occur, yet still controllable. Increase the fluid viscosity and flow rates would be the wise choice to improve the cuttings transport performance in near-vertical holes (Ozbayoglu *et al.*, 2008). However, the removal of drilled cuttings from a wellbore (later known as wellbore cleaning) during drilling highly inclined well has become one of the great challenges in the upstream industry ever since (Ozbayoglu *et al.*, 2008). Hence, the financial benefits become the most concerned among the numerous problems and dangers which surround the drilling process of highly inclined or horizontal holes (Kelin *et al.*, 2013).

These days, drill a directional hole becomes a routine process in all geographic areas around the world, including horizontal holes. On top of that, the economic benefits are firmly established in field practice. Nevertheless, the performance of cuttings transport is reduced with increasing wellbore inclination angle as higher cuttings concentration was discovered in the wellbore (Busahmin *et al.*, 2017). Good hole cleaning demands higher capability of mud to suspend drilled cuttings with slower particle settling velocities, whereas it reversed for directional wells. Besides that, the formation of a cuttings bed becomes dominant as the wellbore inclination angle increases, especially for near-horizontal holes. They also addressed the particle dwell time in the annular space for such wells increased and caused the net volume of cuttings in the wellbore to escalate. Furthermore, several studies have reported that a very complex condition was encountered when drilling directionally, as accumulation of cuttings may result either in the form of stationary bed with hole angle above 50° or in a moving, churning bed with lower hole angles (Sifferman and Becker, 1992; Clark and Bickham, 1994).

Over the past decades, transportation of cuttings in vertical holes have been covered extensively by many researchers with the earliest investigation was delved by Pigott (1941), and continuing (William and Bruce, 1951; Sifferman *et al.*, 1973; Mohammadsalehi and Malekzadah, 2011). Typically, the efficiency of cuttings transportation in vertical holes is influenced by the settling velocity. This settling velocity is dependent on three significant components, namely, cuttings parameters (i.e., cuttings size, density and shape), drilling fluid parameters (i.e., rheology and velocity), and lastly, is operational features such as hole and pipe configurations (Chien, 1994). Studies of cuttings transportation in vertical holes have been well-documented, and not much problem has been recognized, and all are still controllable. Meanwhile, the concern is raised when dealing with directional drilling, especially highly deviated and horizontal holes, due to unexpected problems encountered (Becker and Azar, 1985; Tomren *et al.*, 1986; Okrajni and Azar, 1986). Even though enormous breakthrough and improvement were achieved on that particular drilling covering both experimental (Okrajni and Azar, 1986; Brown *et al.*, 1989; Sanchez *et al.*, 1999) and modelling (Larsen *et al.*, 1997; Hemphill and Ravi, 2010), but the ultimate solution is not yet to be found (Yu *et al.*, 2007).

## 1.2 Statement of Problem

Removal of drilled cuttings out of the hole, which can be termed as a hole cleaning process is vital to ensure a smooth drilling operation. The circulation of drilling fluid is expected to make a ‘downward and upward’ movement. This action may occasionally be true when drilling vertical wells, but it is seldom in the case of drilling high angle holes (Sifferman and Becker, 1992). Since high inclination holes may result in hole cleaning problems, however, it is mandated as the necessity to drill into inaccessible reservoirs, but to deflect the troublesome formations, side-tracking and horizontal drilling require some deviation angles from the vertical (Azar and Sanchez, 1997). Furthermore, the tendency of drilled cuttings accumulation and drop onto the low side of the hole is higher when the hole inclination angle increases. This phenomenon would worsen the torque and drag problems and consequently affect the drilled cuttings lifting efficiency. Therefore, the effect of the hole inclination angle on the effectiveness of cuttings transport is considered in this experimental investigation.

Furthermore, as a common, the production of fine solids becomes an unsurprised issue as drilling into soft and unconsolidated formations. It should be noticed that the fine solid particles generated may lead to poor hole cleaning as it is difficult to lift those particles out of the hole (Duan *et al.*, 2006). The problem worsens as the hole angle and the position of pipe in the hole, i.e., drill string eccentricity, are increasing. Naturally, gravity acceleration leads the drillstring to slide and land on the low side of the hole, where it produces a very low fluid velocity in the narrow gap below that string (Azar and Sanchez, 1997). As in turn, the accumulation of drilled cuttings, especially those of smaller size, will increase in the gap area (Peden *et al.*, 1990). The presence of wellbore pressure complements the formation of cuttings bed as compaction of cuttings takes place and more leads to the pipe sticking. Thus, the consideration to remove the bed erosion is highly appreciable as facilitated by pipe rotation. Sanchez *et al.* (1999) presented the influence of pipe rotation in cuttings bed erosion. The improvement of drilling performance can be attained by optimizing the use of pipe rotation. Therefore, pipe rotation is added as one of the parameters involved in this project to comprehend the effect of pipe rotation on cuttings transport efficiency.

This study was raised as a result of the need for accurate, precise, and realistic data to assist in designing the optimum conditions for drilling fluid used in directional drilling. Consequently, the development of a field-oriented cuttings transport model that accounts for the most important factors affecting particle and fluid dynamics in directional holes is the main objective for this research. Besides that, this experimental investigation also involved the design and fabrication of a cuttings transport flow loop to simulate a drilling rig operation, in order to evaluate the effect of different parameters on hole cleaning while observing the mechanism of cuttings transport. Polypropylene random copolymer beads are added into a basic water-based mud system to improve the performance of cuttings lifting as a requirement of good hole cleaning. Polypropylene copolymer beads, which are lighter than the mud provides a buoyancy force, and the collision between the polymer beads and cuttings has induced an impulsive force, which can significantly improve the efficiency of cuttings transport to the surface.

## 1.3 Hypotheses of Study

The hypotheses of this research works are as follows:

(1) The presence of polypropylene copolymer beads possibly render a slight effect on the mud rheological properties due to its inert properties (chemically inactive), which is a good candidate to be used in the drilling mud, should one intended not to disrupt the mud properties immensely yet have another benefit such as in cutting lifting performance.

(2) The presence of the polypropylene copolymer beads could improve cuttings lifting via buoyancy effect and collision between the cuttings and polymer beads enhance the impulsive force, which accelerates the cuttings upward to the surface.

(3) Drill pipe rotation may plays an important role in improving cuttings lifting performance with polypropylene copolymer beads enriched in water-based mud as it creates a mechanical agitation to shook out the cuttings from bed and yields a whirling and orbital motion to the flowing mud, which accelerates cuttings way up to surface especially in inclined holes, and results in improvement of cuttings lifting.

(4) Increase the drill pipe rotary speed beyond its optimum speed may lead to an insignificant contribution towards cuttings lifting performance.

(5) A turbulent flow could be advantageous in transporting drilled cuttings in directional wells, especially those smaller in size.

## 1.4 Objective of Study

The main focus of this study is to evaluate the effect of using polypropylene copolymer beads as a means to ameliorate Cuttings Transport Performance (CTP), as well as understanding in-depth the influential parameters associated to the cuttings transport problem. Hence, in order to accomplish it, the following objectives have been set explicitly:

(1) To characterize the rheological properties and flow behaviour of basic water-based mud with and without polypropylene copolymer beads.

(2) To improve different sizes of drilled cuttings lifting using polypropylene copolymer beads enriched water-based mud with pipe rotation.

## 1.5 Research Scope

As measures to accomplish the research objectives, the scopes were set forth as follows:

(1) The water-based mud was formulated according to the M-I SWACO industry specification and was prepared with a constant density of 10 ppg each.

(2) The mud rheological properties and fluid loss of 10 ppg water-based mud with and without polypropylene copolymer beads were observed and evaluated.

(3) A cuttings transport flow loop was designed, constructed and commissioned to simulate cuttings transport in an inclined and horizontal wellbore.

(4) Simulated drilled cuttings were collected from Desaru beach, Johor, and their densities were measured using ASTM D4253-16, and a similar standard test method was applied for polypropylene copolymer beads.

(5) The performances of polypropylene copolymer beads in water-based mud to transport drilled cuttings to the surface were analyzed based on the following research variables:

a) Six different sand sizes (simulated cuttings), namely 0.5 – 1.0 mm, 1.0 – 1.4 mm, 1.4 – 1.7 mm, 1.7 – 2.0 mm, 2.0 – 2.8 mm, and 2.8 – 4.0 mm. The mass of simulated cuttings injected into the system was constant throughout the experiment, which was about 0.25% (by volume), approximately 993.75g.

b) Five different concentrations of polypropylene copolymer beads were added into water-based mud, i.e., 2 ppb, 4 ppb, 6 ppb, 8 ppb, and 10 ppb.

c) Six different hole inclination angles were used; vertical (0°), inclined (i.e., 30°, 45°, 60°, and 75°), and horizontal (90°).

d) Five drill pipe rotary speeds were employed, namely 0 rpm, 60 rpm, 90 rpm, 120 rpm, and 150 rpm.

## 1.6 Significance of the Study

High demand for oil and gas, from various industries around the world, has driven the petroleum companies to increase their exploration activities in order to elevate their hydrocarbon production. Thus, one of the approaches is by increasing the measured depths and horizontal displacements of the well to enhance their recovery of crude petroleum from remote and complex reservoirs. Besides that, the technology getting more advanced and sophisticated to ensure the growth of multilateral and high angle wells. However, those technologies still cannot overcome the hole cleaning problems, which become the primary concern of petroleum companies over the past decades until now (Mangor *et al.*, 2008; Egenti, 2014). Numerous novel methods (Li *et al.*, 1999; Mohammadsalehi and Malekzadah, 2011) have been studied to find the best solution to remediate this issue, yet those methods are still not efficient in hindering the occurrence of the problem.

This research investigation was conducted to understand the concept of the removal of drilled cuttings and lift them out of the hole in order to ensure a good hole cleaning in drilling practices. The use of polypropylene copolymer beads in water-based mud is considered because they provide buoyancy force and generate impulsive force due to their collision with drilled cuttings in the circulation fluid. In these conditions, the slip velocity of cuttings would reduce, and the formation of cuttings bed would mitigate significantly. Thereby, it could provide an alternative method to improve the efficiency of hole cleaning. Once the hole cleaning is improved, the rate of penetration (ROP) would increase, which subsequently reduces the Non-Productive Time (NPT) and cost during drilling operations. On that account, the companies' profit will increase, which contributes to the economic development of Malaysia.

## 1.7 Thesis Overview

This dissertation embarks by outlining the broad view of drilling technology advancement concurrently with the increasing demands in petroleum production, which leads to the focus of the research issue – hole cleaning problem. The problem investigation, research's aim and scope of the study, and the reasons for conducting the research work and its importance are unambiguously stated. The overview, as well as the organizational structure of this thesis, are discussed in this section. The thesis comprises five chapters, and each of the chapters is organized as follows.

Chapter 2: Literature Review critically reviews relevant literature on issues pertaining to hole cleaning problems. A table summary of previous works on hole cleaning also embedded in this chapter. Parameters that affect the efficiency of hole cleaning and hole cleaning mechanism in different sections of the wellbore with varying hole inclinations are also discussed to give a tremendous intensive knowledge for the concerning issue. A concise summary is provided in the latter part of the chapter.

Chapter 3: Research Methodology explicates the strategies of research and techniques used in the study and their justification for investigating particular issues highlighted in the literature review. It describes the data collection techniques, the data analysis framework and discusses the limitations of the research. The validation of these methods is crucial as it informs the reader how conclusions in this study have been arrived at.

Chapter 4: Results and Discussion part presents a factual reporting of the research results. These findings are organized around the objectives and within the scope and limitation of the research work. All the data collected are interpreted and analyzed thoroughly, which corresponds to the theory obtained in Chapter 2. A summary of the research findings is presented at the end of this chapter.

Chapter 5 summarizes the thesis with four key conclusions that can be drawn from the collective findings of preceding chapters and reflecting on the extent to which the objectives of the research work were achieved. Recommendations are presented, relying upon the findings and the analysis to help rectify the identified problem. The implications of the research findings are discussed and also include implications for practise as well as implications for future research directions, which can be approached with the tools and understanding developed in this thesis. Findings are incorporated with the theory employed in Chapter 1 and the body knowledge presented in Chapter 2.

## 1.8 Chapter Summary

This chapter presents the overview of the whole thesis, which encompasses the background study, problem statement, hypotheses, objectives, scopes, the significance of the study, and lastly, the thesis overview. This study was conducted to offer an alternative approach by introducing the polypropylene copolymer beads into water-based mud to enhance the transportation of cuttings in the borehole. The problem of hole cleaning has arisen due to an increase in the wellbore inclination angles as more cuttings tend to settle at the lower side of the borehole. However, by injecting the polymer beads to the mud system, it is hoped to increase the buoyancy effect by counteracting the gravitational force imposed on the cuttings and also raising the impulsive force of the cuttings by introducing more polymer beads to collide with the cuttings in the mud system. Previous studies have proved the effectiveness of using polymer beads in the water-based mud to ameliorate the hole cleaning performance, but none was done involving the rotary pipe. Therefore, this research was performed to fill the enigma of employing the pipe rotation to enhance cuttings transport performance.

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